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Author replies to the comments by Anonymous Referee #1:

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We would like to thank Referee #1 for the time she/he has invested into the review of our manuscript. Her/his comments and suggestions have really helped to improve our manuscript. Thank you very much!

Please note: page and line numbers in the updated manuscript might not be the same as in the previously submitted version due to changes in the text as well as due to utilization of a different latex template. The relevant changes in the manuscript are highlighted in red, all removed text is struck through.

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Referee comment:

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This paper presents a modified version of a previously published one dimensional snow model that accounts for canopy influences on snow processes. Although the paper does not add anything fundamentally new to the discourse on snow modeling since the authors mostly just assembled model bits that have already been published, it does constitute credible incremental research that is worth publication. My primary concern is that it is not clear from the data presented that this model substantially improved simulations over the previous version. Since that is the main point, it would be valuable on figures 10 and 11 to show the model results without the modifications (also the associated statistics in table 2).

Answer by the authors:

We thank Referee #1 very much for this valuable comment. Referee #1 is right, it would really be interesting in this context to show the changes between the previous model version (ESCIMO.spread (v1)) and the newly developed ESCIMO.spread (v2). We have followed the reviewer's suggestion and have added the performance of the previous model version to figure 10 and also to table 2 (figure 11 and table 3 in the updated manuscript). However, as the canopy functionality has been added as a new feature in the new model version, it is not possible to show the performance of the previous version with respect to a simulation of inside canopy snow conditions in figure 11 and table 2 (figure 12 and table 3 in the updated manuscript). A discussion of differences in the model results of both versions has been added to the results section (last paragraph of page 19 – first paragraph of page 20) in the updated version of the manuscript.

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Referee comment:

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Eq 13. Does this represent the average wind speed in the canopy? Is it only valid for the part of the canopy above the "canopy reference level" (which I assume is the same as the zero plain displacement height?). Is the wind speed zero below the canopy reference level? Presumably this is equation is only valid away from the canopy edge?

Answer by the authors:

Referee #1 is right, u_c in ESCIMO.spread (v2) represents the average wind speed inside the forest canopy in the respective time interval of 3600s. However, the "canopy reference level" in the equation does not equal the "zero displacement height", but any height in the canopy which the wind speed is calculated for using the exponential function of Cionco (1978). In ESCIMO.spread (v2) this reference level is assumed to be 0.6 * plant height, meaning that we take a calculated wind speed for this level as a representative value for inside canopy conditions. Calculating wind speed for a height below this reference level results in lower values of wind speed, however not necessarily zero. We do not see any indication for this equation being only valid away from the canopy edge.

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Referee comment:
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All the time series figures: Please consider making the y-axis scales better match the maximum values being shown; Figures 6, 8, and 9 have ranges about twice as large as needed – Figure 11 is ok because it matches the companion figure, Figure 10. Also, it would be nice to see plots of predicted vs. observed to better see the range of scatter and whether there are any systematic biases, which I think are really important in evaluating a model.

Answer by the authors:

We thank the reviewer for pointing this out. We followed the referee's suggestion and have adjusted the y-axis in all plots to better match the minimum and maximum values oft the data. For figure 10 and 11 (now figure 11 and 12) we also followed the referee's comment to keep the y-axis similarly scaled to allow better comparison. However, due to the inclusion of the model results achieved with ESCIMO.spread (v1) (as requested by Referee #1, see first comment) we had to rescale the y-axis here as well. We also found the suggestion to include scatter plots very benefitial and have included scatter plots that show the simulations vs the observations for the most important model results (see figure 10 and 13 in the updated manuscript). Thanks again, this was a very fruitfull comment.

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Referee comment:
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While the three evaluation metrics used are ok, I typically like to see something like root mean square error or relative difference, which I think are more meaningful and are easier to interpret than indices that do not really tell me how good predictions are in general; the index of agreement might do this and I am just not as familiar with that statistic.

Answer by the authors:

This is a very good point, we have followed Referee #1's suggestion to include the root mean square error into the performance tables (see table 1-3) and also into the model itself. We have also updated the abstract, the conclusions and the results section with respect to a discussion of root mean square errors. Thanks again, including this efficiency criterion has really improved the manuscript!

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Author replies to the comments by Referee #2:

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The authors would like to thank Referee #2 (Dr. Wolfgang Gurgiser) for helping us to improve our manuscript. Your time and effort is highly appriciated – thank you very much!

Please note: page and line numbers in the updated manuscript might not be the same as in the previously submitted version due to changes in the text as well as due to utilization of a different latex template. All relevant changes in the manuscript are highlighted in red, all removed text is struck through.

GENERAL COMMENTS:

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1. Referee comment:

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Calculating surface snow melt from the surface energy balance means that temperature does not directly control whether there is melt or not. However, in the general model description (p. 8160, lines 10-15) the authors state that air temperature has to be at the melting point temperature of ice. If the model should be an “energy balance snow model” this condition should be removed.

Answer by the authors:

Referee #2 gives a definition of a surface energy balance model that somehow differs from our understanding and that of other members of the hydrological community (e.g. Mauser and Bach (2009) or Warscher et al. (2013)). We think the usage of the term "energy balance model" is not inadequate only because melt conditions are indicated by air temperatures equal or higher than the melting temperature of ice, as long as the actual melt for every time step is calculated on the basis of an energy balance approach. The reason why we derive melt conditions using air temperature as an indicator is due to the fact that we do not explicitly calculate the snow temperature in ESCIMO.spread. If we would do so, we could close the energy balance even for non-melt conditions (snow temperature defines outgoing longwave radiation) and derive melt conditions directly from the calculated energy balance. Without snow temperature beeing calculated for every time step, closing the energy balance is only possible for melt conditions (here assumed for temperatures equal or above the melting point of ice), where snow temperature can be set to the melting temperature of ice allowing closure of the energy balance with melt derived from the available energy at the snow surface.

To leave behind the assumptions described above would require the calculation of snow temperature for every time step and if possible for different snow layers, as currently realized only in the most physically based and complex snow models available (see SNTHERM by Jordan (1991), or CROCUS by Brun et al. (1989) and Brun et al. (1992)). However, due to the computational limitations associated to every spreadsheet-based model, such extensive and complex calculations are hardly realizable in case of the ESCIMO.spread model. To still overcome the deficiencies pointed out by Referee #2, we have implemented a pragmatic approach for estimating the snow temperature proposed by Walter et al. (2005). The method uses negative energy balance values to cool down a single layer snow pack. Although the assumption of a single layer snow pack represents a simplification of real conditions, we have achieved good model performance comparing simulated snow temperature to observations inside the forest canopy at site Vordersteinwald (Nash-Sutcliffe

Model Efficiency (NSME) = 0.57). By impementing this method for calculation of snow temperature into ESCIMO.spread (v2) we are able to close the energy balance for every model time step (even for non-melt conditions), derive melt conditions from the energy balance itself and remove the condition that snow melt is restricted to cases, where air temperature is above or equal the melting point of ice. We thank the referee for bringing this point into the discussion and are glad to have improved the model in this way. The masucript has been updated accordingly (see paragraph 1 on page 6 as well as section 2.3).

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2. Referee comment:

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If I understood correct there is a problem in the model design as described in Section 2.3: From the description of the concept and equation 7 it seems to me that there could be cases where the cold content of the snow is "saturated". If this is true, this would violate energy conservation in any energy balance model. More generally spoken, it seems that this conceptual parametrization cannot be implemented in an energy balance based model approach.

Answer by the authors:

We thank Referee #2 for this valuable comment. He correctly points out that in the conceptual cold content approach implemented in ESCIMO.spread (v2) cases might occur where energy deficits that should further cool down the snow layer might be neglected due to a maximum cold content defined in the model's parameter section. This maximum cold content of course states a violation of energy conservation even though it is suggested in the literature (e.g., Blöschl and Kirnbauer, 1991). We are glad to announce at this point that with the new approach implemented for the calculation of snow temperature (see answer to 1. Referee comment) the cold content of the snow pack can be directly infered from the snow temperature. The original conceptual approach has been removed in the updated version of the model with the manuscript updated accordingly (see section 2.3 (Eq. 6) of the updated manuscript).

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3. Referee comment:

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The implementation of available parametrizations is a good strategy to theoretically show the various impacts of trees on snow cover. I understand that the available measurements (one spot in the presumably very heterogenic canopy) do not allow evaluating the benefit of considering each of the processes individually. However, for the general model evaluation presented in the paper I have the following suggestions: All evaluation of inside canopy model results is based on quality criterions calculated between measurements and individual model results (like global radiation). In my opinion it would be necessary to calculate the increase in model skill when model results/measurements are adapted/not adapted for inside canopy conditions. For example, calculate the increase in skill when modeled inside canopy global radiation is used instead of outside canopy global radiation (similar for temperature, humidity, SWE, wind speed). This strategy would also avoid that high model skills (e.g. high R^2) can (partly) be a result of pronounced daily cycles in both measured and modeled variables (e.g. true for global radiation, temperature etc.).

Answer by the authors:

Referee #2 is right when stating that the efficiency criteria used for evaluating the performance of the canopy submodel (particularly R^2) are biased by daily cycles in many variables e.g. temperature or global radiation. Indeed, the approach proposed by Referee #2 of comparing the efficiency criteria resulting from oposing simulated and observed conditions in the canopy (as done in the submitted manuscript) to those achieved by directly comparing the observed conditions outside the canopy to those observed inside would allow to isolate the increase in model skill from application of the newly implemented canopy model. To put this suggestion into practice, we have calculated the predictive capabilities of outside-canopy observations for inside-canopy conditions for all affected variables (temperature, global radiation, relative humidity, wind speed and snow water equivalent) (see Table 2 in the updated manuscript) and have compared the resulting efficiency values to those achieved using the canopy submodel (see results section in the updated manuscript, last paragraph of page 18 – first paragraph of page 19 as well as first paragraph of page 20). Adding these analyses to our manuscript was an enormous improvement, we thank Referee #2 for this fruitful suggestion.

SPECIFIC COMMENTS:

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1. Referee comment:

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p. 8156, line 4: “a concept for cold and liquid water storage consideration” should be replaced by “a concept for cold content and liquid water storage consideration”

Answer by the authors:

Thanks, we have corrected the manuscript accordingly (see line 2-3, page 2 in the updated manuscript).

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2. Referee comment:

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p. 8156, line 14: “The validation results indicate a good overall model performance in and outside the forest canopy.” “good” could come along with objective quality criterions like RMSE (e.g. “The validation yields good/fair/... results with RMSE of ± xy RMSE [mm WE] / ± xy RMSE [mm WE] for outside / inside canopy conditions. Maybe the authors are also willing to consider this approach in Section 5.

Answer by the authors:

Referee #2 is right, statements like "... good overall performance ..." without providing the respective values of efficiency criteria only provides a subjective perspective on model performance. We have followed the reviewer's suggestion to include efficiency criteria in both the abstract and section 5 (as the Nash-Sutcliffe Model Efficiciency (NSME) is one of the most trusted and common criteria for the quantitative evaluation of hydrological models, we have provided values for this criterion together with values of the RMSE as also proposed by referee #1).

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3. Referee comment:

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In the introduction (p. 8158, lines 5-10) the authors state that the model only requires few input data. Hourly input data of temperature, wind speed, relative humidity, global and longwave radiation are quite expensive in my point of view as this requires a nearby automatic weather station (always limited to one point) or demanding downscaling approaches when using atmospheric model data.

Answer by the authors:

Referee #2 correctly points out that with six required meteorological input variables (precipitation, temperature, wind speed, relative humidity, global radiation and longwave radiation) it might not be adequate to claim ESCIMO.spread requires only few input data. We have therefore rephrased the sentence to (see page 4, line 7 of the updated manuscript): "With hourly recordings of temperature, precipitation, wind speed, relative humidity, global as well as longwave radiation the model's demand on meteorological input is covered by those variables most commonly recorded at any state of the art automatic weather station". Thank you for pointing this out!

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4. Referee comment:

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In the introduction (p. 8158, lines 10-15) the authors state that the model "is even capable of simulating the evolution of a seasonal snow cover under climate change conditions" because temperature and/or precipitation trends can be applied. In my opinion this statement is very optimistic given the fact that (1) e.g. changes in precipitation very likely will also impact air humidity, radiation, temperature etc. and (2) the parametrizations for inside canopy conditions require many empirical parameters. Probably it would be more reliable to write something like "the model is able to calculate simple sensitivity tests for changed temperature/precipitation".

Answer by the authors:

Thank you very much, we have followed your suggestion and have modified the respective section in the manuscript accordingly (see page 4, line 17 in the updated manuscript).

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5. Referee comment:

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P. 8159, line 7: "calculation of the beneath-canopy snow energy and mass balance". If I understood correct (e.g. general comment 2), the model does not always calculate the snow energy balance as the energy balance is not closed in all cases.

Answer by the authors:

Referee #2 is right, in the submitted version of the model and the manuscript, the energy balance could not always be closed due to the design of the implemented cold content concept (see 2nd general comment and the respective answer by the authors). As we have implemented a new approach for the calculation of snow temperature in the updated model version we can now derive the cold content directly from snow temperature. By replacing the old conceptual method for the estimation of the cold content, which led to a violation of energy conservation, with this new approach, the energy balance can now be closed for all cases. Thanks for leading us into the right direction here.

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6. Referee comment:

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p. 8159, lines 5-10 “the new version ESCIMO.spread (v2) reaches beyond the capabilities of most other freely available point-scale snow models”: I’m not sure if this is true as there are meanwhile very sophisticated energy balance models freely available (e.g. http://regine.github.io/meltmodel/). In my opinion the strength of ESCIMO.spread (v2) is that it is very simple/low cost to use and it has extensions to consider inside canopy effects.

Answer by the authors:

Referee #2 correctly states that there are other snow models that share much of the functionality included in ESCIMO.spread (v2), however these models in most cases are not spreadsheet-based point-scale snow models. While the fact that we are refering to point-scale models was included in the submitted manuscript, we have added "spreadsheet-based" in the updated manuscript (see page 5, line 10 in the updated manuscript). Thank you very much for helping us to improve this part of the manuscript. Clearly, the fact that ESCIMO.spread (v2) accounts for canopy effects is one of its strengths, however no modifaction in the mansucript was neccessary here as the last three items in the list of the models key features already refer to this model strength emphasised by Referee #2 (see p. 8159, line 3 – 8 in the previously submitted manuscript).

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7. Referee comment:

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In 2.2 wet bulb temperature is used to separate solid from liquid precipitation which is definitely a reliable approach. Nevertheless, it would be interesting to see the relative differences (%) in calculated snow fall amount for one winter when applying the dry bulb instead of the wet bulb temperature. Thereby it seems important that the relative humidity measurements are bias corrected (nearly 100% RH should be reachable in case of very wet conditions). Furthermore, it could be an idea to interpolate from 100% solid to 100% liquid precipitation for a given range of wet bulb temperature (e.g. 0±0.5 degree) to avoid jumps in the calculated snow fall amounts

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Answer by the authors:

Referee #2 correctly states that it would be interesting to see the difference in solid precipitation when applying i) the air temperature-based approach for separation of liquid and solid precipiatation and ii) the wet-bulb temperature-based approach. We have done this comparison for site Vordersteinwald and the winter 2012/2013. We found out that using a wet-bulb temperature treshold of 273.16 K results in 43% less solid precipitation compared to using an air temperature treshold of 275.16 K (273.16 K wet-bulb temperature equals 273.16 K air temperature for air humidities around 70%, see figure 2 of the manuscript). We have chosen these tresholds as the wet-bulb temperature of 273.16 K is used in the current study as a default value and 275.16 K is a common air temperature treshold for precipitation phase detection and also the default value in the ESCIMO.spread model (v1) (see Strasser and Marke 2010). As this comparison strongly depends on the chosen threshold for both temperature criteria and the results are hence of little general validity, we have not included this information in the updated version of the manuscript. If the editors feel, this information would improve the manuscript, the authors are of course willing to add this information in the final version of the paper.

With respect to the relative humidity values we agree that the fact that 100% are never reached (maximum = 97 %) might be the result of biases in the recorded data. However, Pohl et al. (2014) have shown that the applied SnoMoS over the whole range of possible humidity values generally rather tend to overestimate than to underestimate actual air humidity. Hence, setting the maximum values in the time series to 100% (as often done to correct humidty time series) will result in the desired increase of maximum humidity values, but might also lead to increased overestimation in the mid-range values. We therefore think modifying these measurements would only bring little benefit coming along with increased overall uncertainty. Moreover, certain biases can also be expected in case of many other recorded variables (see Pohl et al. 2014) with a correction of all variables clearly reaching beyond the scope of this study. The decision not to modify the data is further supported by the fact that we checked in- and outside relative humidity to be similarly biased to maximum values of about 97%. Hence, we can exclude additional biases in the model results that might be induced by different accuracies of in- and outside measurements. To test the impact of applying a correction factor (that modifies all humidity data so that the maximum values reach 100%) on the simulated snow cover we have implemented a correction of observed outside-canopy humidity (observed inside-canopy humidity is not used by the model as humidity in the forest is derived from outside measurements) into the model. The results show only an insignificant impact on the model results with the Nash-Sutcliffe Model Efficiency (NSME) staying unchanged in case of outside-canopy SWE (NSME=0.71) and with NSME even slightly decreasing from 0.81 to 0.80 for inside-canopy SWE. If the editors nevertheless consider it important to correct the applied humidity measurements, the authors are willing to include a correction of measured humidity also in the submitted version of the model. In the updated version of the manuscript, potential biases in the measurements are shortly adressed in the conclusions (see line 6 on page 22 of the updated manuscript).

Referee #2 also suggests to include a certain temperature range where both liquid and solid precipitation exist to certain shares. We aggree that this approach might (under certain circumstances and at some sites) lead to better model results as sudden changes in precipitation phase are smoothend out. We have therefore extended the model with this functionality making this temperature range a user-defined parameter in the model's parameter section. As the application of the proposed value of +- 0.5 K has negatively affected the model results at site Vordersteinwald in a test run, we have not used a temperature range for precipitation phase detection in this study, but describe the new functionality in the updated version of the manuscript (see first paragraph of page 8 in the updated manuscript).

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8. Referee comment:

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In Section 2.3 (besides issue 2 in the general comments) it was challenging for me to think of a cold content expressed in units [- mm w.e.]. From my point of view a cold content in an educational tool would be better related to negative temperatures [degree C] of the snow pack (or certain layers) that can – together with the snow mass – be converted into energy content [J]. In a second step this would allow to calculate the energy [J] that is required to heat the snow pack up to the melting point temperature.

Answer by the authors:

Referee #2 proposes to change the unit of the cold content from [mm] to [°C]. From our point of view the favoured unit of the cold content strongly depends on the personal scientific background of the model user and could be [mm], [°C] or even [J] as all somehow describe the energy level of the snow pack - these units can also easily be converted from one unit to the other. From a snow modeller's perspective and also from an educational point of view, the unit [mm] also seems adequate as it is the amount of water that reduces melt for a certain time step due to the actual cold content of the snow pack. As we also agree that judging from the name "cold content" itself the unit [°C] does really make sense as well, we have extended the model so that the cold content now is provided in [mm] as well as in [°C]. We thank the reviewer for his suggestion, we think it really improved the model.

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9. Referee comment:

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Section 4 and Fig. 8: It looks like there is an obvious bias in the RH measurements as the values never reach (nearly) 100%. Please also do a bias check for the outside canopy RH measurements.

Answer by the authors:

See the authors’ response to specific comment 7.

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10. Referee comment:

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In the results section the authors rarely comment on Fig. 10 (especially on the second pronounced snow pack in February 2013) which is essential as it shows the model capacity to reproduce outside canopy snow pack without any complications induced by the forest. If the model skill is higher inside the forest than outside (table 2) this could suggest that it is easier to model inside canopy conditions. However, I don’t think that this is true but a result of (1) multiple error compensation effects (including errors in precipitation derived from a distant gauge) and (2) at least partly coincidence as there seems to be only 1 point measurement available in the canopy which does not represent the expectable strong spatial heterogeneity. The latter aspect is a serious issue for all the inside canopy evaluation and for future studies it would be desirable to do some small scale (e.g. within a couple of meters) cross section measurements of (at least) SWE inside the canopy.

Answer by the authors:

Referee #2 points out that the snow simulations outside the canopy as well as the arising differences between the model performance in- and outside the forest canopy should be discussed in more detail. We fully aggree with the referee's line of argumentation explaining the fact that the model results inside the canopy are better than outside at least partly through error compensation effects (including errors from precipitation measurement and the transfer of precipitation information from precipitation gauge Freudenstadt to site Vordersteinwald). We also aggree that it is surprising that a single SWE measurement in the forest can be this close to the simulations, given the expectable heterogenity of snow cover inside forests. To get deeper insights into the spatial snow cover heterogenity inside forests we have just recently installed multiple snow depth measurement units inside different forest sites in the Alpine catchment Brixenbachtal (Tyrol, Austria). The resulting data will be very valuable in future studies, as also pointed out by Referee #2. Following the referee's suggestion to extend the discussion on differences in the model results in- and outside the canopy we have updated the manuscript accordingly (see results section (page 20) and conclusions (first paragraph, page 22)). We thank the referee for pointing out this issue.

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11. Referee comment:

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p. 8172, lines 1-5: The lower R^2 for RH and wind speed might be a result of the weaker or missing daily cycles (see also general comment 3). Please also think again about potential offsets in the RH measurements (Fig. 8).

Answer by the authors:

We share Referee #2's perception that the lower values of R^2 might be a result of weaker or missing daily cycles in wind speed and have added this information to the updated version of the manuscript (see last paragraph page 18 - first paragraph page 19 as well as first paragraph of page 22 in the updated manuscript). With respect to the offset in humidity values please refer to the 7th general comment and the respective answer of the authors.

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12. Referee comment:

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p. 8174, line 23: I think "trend" should be replaced by "patterns".

Answer by the authors:

Thank you very much, we have followed you suggestion and have replaced "trend" by "patterns" in the updated version of the manuscript (see 2nd line of page 23 in the updated manuscript).

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13. Referee comment:

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Fig. 2 and 3 could be moved to an appendix to better focus on the results (Fig. 4 and Figs. 6-11).

Answer by the authors:

We thank Referee #2 for his suggestion, however we think that figure 2 and 3 are very valuable in the context of the implemented approach for wet-bulb temperature calculation. We therefore would like to leave them in the model description section and have not changed the manuscript with respect to the location of these figures.

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14. Referee comment:

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Fig. 2: “rain” and “snow” are a bit confusing in this plot. Maybe the authors could add a sentence from Section 2.2 (“Each of the displayed lines in Fig. 2 could be interpreted as a borderline to separate liquid and solid precipitation assuming a certain threshold wet-bulb temperature”) in the legend instead. Please also consider again if it would make sense to implement a temperature range to gradually shift from 100% solid to 100% liquid precipitation.

Answer by the authors:

If we interpret the referee’s comment correctly, Referee #2 would prefer the terms "liquid precipitation" and "solid precipiation" to "rain" and "snow" in Fig. 2. Moreover, he proposes to add text to the legend explaining the meaning of the shown lines. We have changed the terms "rain" and "snow" to "liquid precipiatation" and "solid precipitation" in an updated version of Fig. 2. As we think that an explanatory text would better fit into the caption of Fig. 2 than into the legend, we have updated the caption of Fig. 2 accordingly.

Referee #2 also suggests to include a certain temperature range in the model where both liquid and solid precipitation exist to certain shares. We have updated the model accordingly, for details please see the 7th general comment and the respective answer of the authors. We thank the referee for these valuable suggestions.

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15. Referee comment:

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Fig. 6: Maybe a scatter plot of the daytime values could better show the model skill. Currently, it is very hard to distinguish between the lines. Another idea could be to compare mean daily values.

Answer by the authors:

We see that it is hard to distinguish between the grey and black lines in Fig. 6 and have therefore updated all line plots with respect to the colors of the different time series. The colored lines are now much easier to distinguish. Moreover, we have followed Referee #2’s suggestion to show the data in form of scatter plots (see figure 10 and 13 in the updated manuscript). This was also suggested by Referee #1. Thank you very much, these changes represent a big improvement of the manuscript.

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Note to the Editorial team:

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Dear members of the Editorial team,

We are glad to inform you that we have adressed all comments by the referees and have updated the model and the manuscript accordingly. We really believe these modifications represent significant improvements of our work and hope the updated version of our manuscript can now be published without further modification.

Please note: page and line numbers in the updated manuscript might not be the same as in the previously submitted version due to changes in the text as well as due to utilization of a different latex template. All relevant changes in the manuscript are highlighted in red, all removed text is struck through.

Besides the content-related changes proposed by the two referees, we have improved the manuscript with respect to the following formal issues:

- Equations, figures and tables have not always been similarly adressed ("see equation (1)" vs "see Eq. 1"). We have therefore updated the manuscript so that equations, tables and figures are now all referred to in the text by "Eq. X", "Fig. X" and "Tab. X" when located in the middle of a sentence and by "Equation X", "Figure X" and "Table X" when placed at the beginning of a sentence.
- We have observed that multiplications have been expressed differently ranging from usage of no operator, over usage of "x" to usage of "·". We have updated the manuscript so that every multiplication is now formulated by using "·".

Thank you very much for all your efforts,

Best regards,

The authors

Manuscript prepared for Geosci. Model Dev. Discuss.
with version 2014/09/16 7.15 Copernicus papers of the LaTeX class copernicus.cls.
Date: 31 December 2015

ESCIMO.spread (v2): parameterization of a spreadsheet-based energy balance snow model for inside-canopy conditions

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Abstract

This article describes the extension of the spreadsheet-based point energy balance snow model ESCIMO.spread by (i) an advanced approach for precipitation phase detection, (ii) a method for cold content and liquid water storage consideration and (iii) a canopy sub-model that allows to quantify the effect of a forest canopy on the meteorological conditions inside the forest as well as the simulation of snow accumulation and ablation inside a forest stand. To provide the data for model application and evaluation, innovative low-cost Snow Monitoring Systems (SnoMoS) have been utilized that allow the collection of important meteorological and snow information in- and outside the canopy. The model performance with respect to both, the modification of meteorological conditions as well as the subsequent calculation of the snow cover evolution are evaluated using in- and outside-canopy observations of meteorological variables and snow cover evolution as provided by a pair of SnoMoS for a site in the Black Forest mountain range (south-west Germany). The validation results for simulated snow water equivalent with Nash-Sutcliffe Model Efficiency values of 0.81 and 0.71 and root mean square errors of 8.26 and 18.07 mm indicate a good overall model performance in- and outside the forest canopy, respectively. The newly developed version of the model referred to as ESCIMO.spread (v2) is provided free of charge together with one year of sample data including the meteorological data and snow observations used in this study.

1 Introduction

In forested areas significant variations in snow accumulation can result from the processes of forest canopy interception and sublimation of intercepted snow (Marsh, 1999; Pomeroy et al., 1998). Snowfall in forested areas is either intercepted by stems, needles and branches or passes through the canopy directly reaching the underlying forest floor. Due to its large surface area exposed to the surrounding atmosphere, intercepted snow can be subject to high sublimation losses, especially in dry continental climates. Generally, sublimation losses of previously intercepted snow can be as high as 30 % of snow precipitation, depending on the efficiency of interception, its duration and the atmospheric boundary conditions (Liston and Elder, 2006b; Pomeroy and Gray, 1995; Strasser et al., 2008). Intercepted snow can also be removed from the canopy by direct unloading and dripping of meltwater to the ground (Liston and Elder, 2006b; Pomeroy et al., 2002). Compared to snow in the open, snow in forest canopies is exposed to different meteorological conditions. It is sheltered from wind and incoming shortwave radiation while receiving increased longwave radiation emitted from the surrounding trees (Link and Marks, 1999a, b). Likewise, humidity and temperature underneath a canopy differ from those in the open (Liston and Elder, 2006b). In the boundary layer, forest canopies moreover strongly modify the interactions between snow-covered surfaces and the atmosphere. Even the litter on the forest floor has a significant effect on the radiative properties of the snow cover beneath a canopy (Melloh et al., 2002; Hardy et al., 2001).

The influences of a forest canopy on the snow cover dynamics beneath are very complex. The snow cover duration in the forest depends on various factors. A delay of the spring snow melt under a dense forest canopy compared to open areas due to the reduction of incoming solar radiation was shown by Link and Marks (1999a). On the other hand shorter snowpack duration in the forest was observed by Dickerson-Lange et al. (2015). Strasser et al. (2011) showed in a numerical modelling experiment for a virtual mountain that in snow-rich winters, the shadowing and its protective effect is dominant. In winters with little snow, snow sublimation losses become dominant and, consequently, the snow lasts longer in the open than inside the forest, mainly for northern exposures (in the Northern Hemisphere). Similar patterns were observed by Pohl et al. (2014) in the Black Forest region.

To develop a free and easy to use tool for the simulation of the temporal evolution of the snow cover with explicit consideration of these complex snow-canopy-atmosphere interactions, the spreadsheet-based point energy balance snow model ESCIMO.spread developed by Strasser and Marke (2010) (in the following referred to as ESCIMO.spread (v1)) has been extended with a canopy sub-model. Moreover, the model has been improved by integrating an advanced algorithm for precipitation phase detection that applies wet-bulb temperature as a criterion to distinguish solid and liquid precipitation. Another model improvement is a new parameterization for cold and liquid water content of the snow cover allowing to consider refreezing of liquid precipitation or meltwater in the snowpack. Compared to other existing spreadsheet-based snow models (e.g. the glacier and snow melt study model by Brock and Arnold, 2000) ESCIMO.spread (v2) is particularly fast and can easily be modified by simple change of the parameters and formulae with results immediately visualized. With hourly recordings of temperature, precipitation, wind speed, relative humidity, global as well as longwave radiation the model's demand on meteorological input is covered by those variables most commonly recorded at any state of the art automatic weather station. While Walter et al. (2005) have presented a spreadsheet energy balance model that requires even less meteorological input data (daily minimum/maximum temperature and precipitation), their approach operates at a daily time step only and does not allow to quantify sub-daily variations in snow cover conditions. Moreover, compared to the canopy model implemented in ESCIMO.spread (v2), the consideration of canopy effects in the Walter et al. (2005) model is reduced to a canopy-induced extinction of solar radiation only. Canopy effects on other meteorological variables or vegetation-snow cover interactions (e.g. the interception of snow in the canopy) are not accounted for. By providing the option to define trends in precipitation and/or temperature in the models parameter section, ESCIMO.spread allows to calculate sensitivity tests for changes in temperature and precipitation for any site of interest. As ESCIMO.spread (v2) is in simple table format and does not include any macros it can be applied by all common spreadsheet programs (e.g., Microsoft Excel, Apple Numbers, OpenOffice Calc) on a variety of platforms (Windows, Linux, Mac OS). Due to its simplicity, ESCIMO.spread (v2) is particularly suitable for application in education (e.g., in practically-oriented student courses) and can even be operated with laptop computers, e.g. to visualize and plausify measured meteorological parameters and the simulated snow cover directly in the field.

With its new features of

- sophisticated precipitation phase detection using a wet bulb temperature threshold,
- snow temperature estimation,

- cold content and liquid water content calculation with consideration of refreezing of water from melt or liquid precipitation, and meltwater outflow,
- transformation of standard meteorological observations (precipitation, relative humidity, temperature, wind speed, global radiation) from the open into conditions inside a forest canopy,
- calculation of snow interception and subsequent sublimation, melt or dropping of intercepted snow to the ground and
- calculation of the beneath-canopy snow energy and mass balance,

the new version ESCIMO.spread (v2) reaches beyond the capabilities of most other freely available point-scale spreadsheet-based snow models and can be expected to set forth the history of ESCIMO.spread as a well-accepted, documented and freely available snow model for application in both science and education. This paper describes the newly implemented algorithms and evaluates the model results against available hydrometeorological observations in- and outside the forest canopy at a site in the Black Forest mountain range (south-west Germany, see Fig. 1) with a mostly temperate snow cover in an elevation of 800 m a.s.l. The applied hydrometeorological data have been recorded by a set of low-cost snow monitoring systems (SnoMoS) recently developed by Pohl et al. (2014). The model can be downloaded from www.alpinehydroclimatology.net together with one year of example meteorological recordings and snow observations.

2 The ESCIMO.spread model (v2)

2.1 General description

The new version ESCIMO.spread (v2) builds upon the ESCIMO.spread model as published by Strasser and Marke (2010). It is a 1-D, one-layer process model which calculates snow accumulation and melt for a snow cover assumed to be a single and homogeneous pack. To do so, it solves the energy and mass balance equations for the snow surface applying simple parameterizations of the relevant processes. The energy balance of the snow surface is calculated for each hourly time step considering short- and longwave radiation, sensible and latent heat fluxes, energy conducted by solid or liquid precipitation as well as sublimation/resublimation and a constant soil heat flux (Strasser and Marke, 2010). Thereby, absorbed and reflected shortwave radiation is calculated from incoming shortwave radiation on the basis of the snow albedo, which is estimated for each hourly time step using an albedo ageing curve approach. Solid precipitation increases the amount of snow water equivalent (SWE) on the land surface, while liquid precipitation is (up to a certain maximum amount depending on actual SWE) added to the liquid water storage of the snowpack. While melt in ESCIMO.spread (v1) has been calculated from the energy balance remainder only if air temperature exceeds 273.16 K, the newly implemented method for snow temperature estimation (see section 2.3) allows to remove this condition in ESCIMO.spread (v2). The model results are visualized in the form of diagrams for the majority of model variables, together with four quantitative measures of goodness of fit.

2.2 Precipitation phase detection

The new version ~~of~~ ESCIMO.spread (v2) includes an improved distinction between liquid and solid precipitation. As air temperature T_a is often an insufficient indicator for the precipitation water phase (Steinacker, 1983), wet-bulb temperature T_w is used in ESCIMO.spread (v2) as a combined measure of air temperature and humidity to distinguish liquid from solid precipitation. Figure 2 shows the relation between air temperature, wet-bulb temperature and relative humidity for different altitudes to account for the dependence of wet-bulb ~~pressure~~ temperature on air pressure. Each of the displayed lines in Fig. 2 could be interpreted as a borderline to separate liquid and solid precipitation assuming a certain threshold wet-bulb temperature. Largest differences between air temperature and wet-bulb temperature occur at low air humidities, clearly pronouncing the added value associated to application of wet-bulb temperature as a criterion for phase detection.

Generally, wet-bulb temperature can be derived by solving the psychrometric equation

$$e_\mathrm{a}(T_\mathrm{a}) - e_\mathrm{s}(T_\mathrm{w}) - A\cdot(T_\mathrm{a} - T_\mathrm{w}) = 0 \tag{1}$$

for T_w (K), where A (Pa K^{-1}) is the psychrometric constant, and $e_\mathrm{a}(T_\mathrm{w})$ (Pa) and $e_\mathrm{s}(T_\mathrm{w})$ (Pa) the vapor pressure of the air and the saturation vapor pressure at wet-bulb temperature, respectively. As there is no explicit solution to the psychrometric equation (Campbell and Norman, 1998) and iterations are unfavourable in a spreadsheet model, a pragmatic assumption has been made: for a broad range of combinations of air temperature and relative humidity values, lookup tables have been generated outside the spreadsheet model using an iterative solution scheme for Eq. (1). Beside temperature and humidity, wet-bulb temperature also depends on air pressure p_z (Pa) which is required to calculate the psychrometric constant, A, as (Kraus, 2004)

$$A = \frac{p_z\cdot c_\mathrm{p}}{0.622\cdot L_\mathrm{v}}, \tag{2}$$

where c_p is the specific heat capacity of air at constant pressure (1004 J kg^{-1} K^{-1}) and L_v (J kg^{-1}) represents the latent heat of vaporization. In ESCIMO.spread (v2) the temperature dependence of the psychrometric constant is neglected since this dependency is by far less important compared to that associated to air pressure at higher altitudes (Kraus, 2004; Campbell and Norman, 1998). Air pressure, p (Pa), at a given elevation, z (m), can be derived from standard atmospheric pressure, p_0 (Pa), by integration of the hydrostatic equation assuming a linear decrease of temperature with increasing altitude ($\gamma = -0.0065$ K m^{-1})

$$p_z = p_0 \left[\frac{T_\mathrm{a}}{T_\mathrm{a} - \gamma\cdot z}\right]^{-\frac{g}{\gamma\cdot R}}, \tag{3}$$

where R is the gas constant of dry air (287 J kg^{-1} K^{-1}) and g is gravity (m s^{-2}). To account for the air pressure dependence, the implemented lookup tables have been prepared for several elevation bands with a 500 m interval. Figure 3 shows a comparison of wet-bulb temperatures calculated using the lookup table approach to those achieved with an iterative solution for different elevations. The differences between both approaches shown for a common snowfall situation are relatively small. Therefore, the lookup table approach allows a sufficiently accurate estimation of wet-bulb temperature in the model. The threshold for wet-bulb temperature as required for precipitation phase detection in ESCIMO.spread (v2) is one of the user-defined input parameters and is here set to 273.16 K. To avoid sudden changes in precipitation phase when temperatures fall below the defined temperature threshold, in ESCIMO.spread (v2) a temperature range can be defined (e.g. 273.16 +/- 0.5 K) in which liquid precipitation decreases from 100 to 0 % with solid precipitation increasing accordingly. When temperature is exactly at the defined temperature threshold (here 273.16 K) this approach results in 50 % liquid and 50 % solid precipitation.

2.3 Cold and liquid water content

A physically based method for estimating the snow temperature and deriving the cold content of a single layer snow pack has been implemented in ESCIMO.spread (v2) following an approach presented by Walter et al. (2005). The snow temperature T_s (K) for a given time step is derived using the snow temperature calculated for the previous time step, T_{st-1} (K), and a temperature change $\mathrm{d}T$ (K) as

$$T_s = \min\{T_{st-1} + \mathrm{d}T, 273.16\}. \tag{4}$$

The temperature change in Eq. 4 is derived as

$$\mathrm{d}T = \frac{E_{t-1} \cdot \mathrm{d}t + \mathrm{RF}_{t-1} \cdot c_\mathrm{i}}{(\mathrm{SWE}_{t-1} + P_s) \cdot c_s} \tag{5}$$

where E_{t-1} (W m^{-2}) is the energy balance of the previous time step, $\mathrm{d}t$ (s) is the time step length, RF_{t-1} (mm) is the liquid water refrozen in the previous time step, c_i is the melting heat of ice (3.337×10^5 J kg^{-1}), SWE_{t-1} (mm) is the SWE of the previous time step, P_s (mm) is the solid precipitation in the current time step and c_s is the specific heat of snow (2100 J kg^{-1}K^{-1}).

Using this approach, heat losses resulting from a negative energy balance can be used to build up a cold content, which represents the amount of energy required to increase snow temperature to 273.16 K. Snow temperature and cold content can be considered as equivalent and physically consistent representations of the snow pack's energy state as defined by Eq. 6. The cold content first needs to be reduced to zero by positive energy inputs before actual melt can occur. By implementing a concept for liquid water content as proposed by Braun (1984) and Blöschl and Kirnbauer (1991), melting snow is not immediately removed from the snowpack, but a certain amount of liquid water can be retained (and possibly refreeze again). Combining these approaches for cold content estimation and liquid water content consideration allows to account for the delay between beginning surface melt and drainage of a snow cover.

The cold content C_c (mm) for each model time step is infered directly from calculated snow temperature in the form of

$$C_\mathrm{c} = \frac{(T_s - 273.16) \cdot (\mathrm{SWE}_{t-1} + P_s) \cdot c_s}{c_i}. \tag{6}$$

In the case of a negative energy balance, a refreezing of liquid water in the snowpack, RF (mm), is calculated in the form of

$$\mathrm{RF} = \min\left\{C_{\mathrm{lw}t-1}, (-E \cdot \mathrm{d}t)/c_\mathrm{i}\right\}, \tag{7}$$

where $C_{\mathrm{lw}t-1}$ (mm) is the liquid water content of the previous time step. C_lw for a given time step can be derived as

$$C_\mathrm{lw} = C_{\mathrm{lw}t-1} + P_\mathrm{l} - \mathrm{RF}, \tag{8}$$

where P_l (mm) is liquid precipitation.

In the case of a positive energy balance, actual melt, M (mm), is calculated considering the change in cold content between the actual and the previous time step as

$$M = \min\{(E \cdot \mathrm{d}t/c_\mathrm{i}) - (C_\mathrm{c} - C_{\mathrm{c}t-1}), (\mathrm{SWE}_{t-1} - C_{\mathrm{c}t-1})\}. \tag{9}$$

C_lw is then updated in the form of

$$C_\mathrm{lw} = \min\{C_{\mathrm{lw}t-1} + M, \mathrm{SWE}_{t-1} \cdot \mathrm{HC_w}\} \tag{10}$$

where $\mathrm{HC_w}$ $(-)$ is a water holding capacity that limits liquid water storage and is specified as a fraction of the total snowpack weight. This parameter is to be defined by the user in the model's parameter section and set to $\mathrm{HC_w} = 0.1$ as recommended by Blöschl and Kirnbauer (1991) by default.

Finally, the outflow (i.e. the excess water that is actually removed from the snowpack), O (mm), can be calculated as

$$O = \max\{(C_{\mathrm{lw}t-1} + P_\mathrm{l} + M) - \mathrm{SWE}_{t-1} \cdot \mathrm{HC_w}, 0\}. \tag{11}$$

2.4 Modification of meteorological conditions inside the forest canopy

The canopy model newly implemented in ESCIMO.spread (v2) by Liston and Elder (2006b) has already been successfully applied under alpine conditions (see Strasser, 2008 or Strasser et al., 2011). The development of the approach was motivated by the fact that meteorological observations inside forest canopies only sparsely exist necessitating the estimation of inside-canopy conditions from availabe meteorological observations in the open. The method requires information on leaf area index and canopy height which can either be derived from field measurements or be taken from literature for a wide range of plant species (e.g. from Breuer et al., 2003, or Liston and Elder, 2006b).

Wind speed inside the canopy u_c ($\mathrm{m\,s^{-1}}$) is derived from above-canopy wind speed u ($\mathrm{m\,s^{-1}}$) as (Cionco, 1978)

$$u_\mathrm{c} = u \exp(-a \cdot (1 - z/h)), \tag{12}$$

where h (m) is the canopy height and z (m) is the canopy reference level assumed to be 0.6 h (Liston and Elder, 2006b; Essery et al., 2003).

The canopy flow index, a $(-)$ is calculated as a function of the effective leaf area index, LAI* (m^2 m^{-2}), and a scaling factor, β $(= 0.9)$ that is introduced by Liston and Elder (2006b) to make LAI* compatible with the canopy flow index proposed by Cionco (1978):

$$a = \mathrm{LAI}^{*} \cdot \beta \tag{13}$$

LAI* includes stems, leaves and branches as described by Chen et al. (1997).

To consider the extinction of solar radiation by the forest canopy, top-of-canopy incoming shortwave radiation, Q_{si}, is reduced following the Beer–Lambert law as

$$Q_{\mathrm{sif}} = Q_{\mathrm{si}} \cdot \tau_{\mathrm{v}}, \tag{14}$$

where Q_{sif} is the incoming shortwave radiation impinging on the snow surface beaneath the canopy (Hellström, 2001). τ_{v} representing the fraction of Q_{si} reaching the land surface is derived as

$$\tau_{\mathrm{v}} = \exp(-k \cdot \mathrm{LAI}^{*}), \tag{15}$$

with k being a vegetation-dependent extinction coefficient (Liston and Elder, 2006b). Aiming at a best fit to observed radiation inside forest canopies of different species (e.g. spruce, subalpine fir, pine) at a site in the U.S. Department of Agriculture (USDA) Fraser Experimental Forest near Fraser (Colorado, USA), Liston and Elder (2006b) have yielded best overall performance using a k value of 0.71, which is also used for the simulations here.

Incoming longwave radiation inside the canopy is assumed to be composed by a fraction F_{g} $(-)$ directly reaching the ground through gaps in the forest stand and a fraction F_{c} $(-)$ emitted by the forest canopy. The canopy-emitted fraction is calculated following Liston and Elder (2006a) as

$$F_{\mathrm{c}} = a + b \cdot \ln(\mathrm{LAI}^{*}) \tag{16}$$

where a $(-)$ and b $(-)$ are constants with values of 0.55 and 0.29, respectively. A value of F_g can be derived as

$$F_\mathrm{g} = 1 - F_\mathrm{c}, \tag{17}$$

with both calculated fractions used to estimate inside-canopy incoming longwave radiation Q_lif ($\mathrm{W\,m^{-2}}$) from

$$Q_\mathrm{lif} = (F_\mathrm{g} \cdot Q_\mathrm{li}) + (F_\mathrm{c} \cdot \sigma \cdot T_\mathrm{c}^4), \tag{18}$$

where Q_li ($\mathrm{W\,m^{-2}}$) represents the top-of-canopy incoming longwave radiation. The latter is provided as input for ESCIMO.spread (v2) and is here estimated as a function of temperature and cloud cover as proposed by Liston and Elder (2006a) due to a lack of observations. σ represents the Stefan Boltzmann constant and T_c (K) the inside-canopy temperature. Assuming a linear dependency on canopy fraction, T_c is derived from top-of-canopy temperature T_a (K) as proposed by Obled (1971):

$$T_\mathrm{c} = T_\mathrm{a} - F_\mathrm{c} \cdot (T_\mathrm{a} - (R_\mathrm{c} \cdot (T_\mathrm{a} - T_\mathrm{mean}) + T_\mathrm{mean} - \delta T)), \tag{19}$$

where T_mean (K) is the mean daily air temperature, R_c $(-)$ is a dimensionless scaling parameter set to 0.8 and $\delta T(-2\,\mathrm{K} \leq \delta T \leq +2\,\mathrm{K})$ is a temperature offset defined to be (Durot, 1999)

$$\delta T = \frac{T_\mathrm{mean} - 273.16}{3}. \tag{20}$$

Durot (1999) has further shown that relative humidity inside the canopy, $\mathrm{RH_c}$ (%), is often higher compared to the open due to sublimation and evaporation of melted snow. We therefore propose to modify top-of-canopy humidity RH (%) with consideration of the canopy fraction in the form of (Durot, 1999)

$$\mathrm{RH_c} = \max\{\mathrm{RH} \cdot (1 + 0.1 \cdot F_\mathrm{c}), 100\}. \tag{21}$$

2.5 Simulating canopy effects on the snow cover

The following describes the newly implemented approaches to describe snow interception through the forest canopy as well as melt-induced unloading of intercepted snow from the canopy.

Interception of solid precipitation, P_s (mm) at time t is derived introducing a canopy-intercepted load, I (mm), expressed as (Pomeroy et al., 1998)

$$I = I_{t-1} + 0.7 \cdot (I_{\text{max}} - I_{t-1}) \cdot (1 - \exp(-P_s / I_{\text{max}})), \tag{22}$$

where $t-1$ represents the previous time step and I_{max} is the maximum interception storage calculated as (Hedstrom and Pomeroy, 1998)

$$I_{\text{max}} = 4.4 \cdot \text{LAI}^*. \tag{23}$$

Sublimation of intercepted snow Q_{cs} (mm) is calculated as described by Liston and Elder (2006b) as

$$Q_{\text{cs}} = C_{\text{e}} \cdot I \cdot \Psi_{\text{s}} \cdot \text{d}t, \tag{24}$$

where $\text{d}t$ (s) is the time increment (here: 3600 s), Ψ_{s} (s^{-1}) is the sublimation-loss rate coefficient for an ice sphere and $C_{\text{e}}(-)$ represents the canopy exposure coefficient. Ice spheres are assumed to be characterized by a constant radius of 500 µm as proposed by Liston and Elder (2006b).

The canopy exposure coefficient is calculated as

$$C_{\text{e}} = k_{\text{c}} \cdot (I / I_{\text{max}})^{-0.4}, \tag{25}$$

where k_{c} $(-)$ is a dimensionless coefficient related to the shape of the intercepted snow deposits (Liston and Elder, 2006b). Sublimation at the canopy scale is hence estimated based on sublimation from individual ice spheres. Analysing observed (Montesi et al., 2004) and modelled sublimation rates for a 2.7 m-tall subalpine fir tree at the USDA Fraser Experimental Forest, Liston and Elder (2006b) have found that the application of $k_\mathrm{c} = 0.010$ seems to best reproduce observed sublimation rates at both, higher an lower elevated tree sites. This value is very close to the value of $k_\mathrm{c} = 0.011$ derived by Pomeroy et al. (1998) for Canadian Boreal Forest and is used as k_c value for the calculations with ECIMO.spread (v2) here. This parameter can be easily adapted by changing the respective setting in the parameter section of the model.

The sublimation-loss rate coefficient Ψ_s is calculated from the particle mass m (kg) in the form of

$$\Psi_\mathrm{s} = (\mathrm{d}m/\mathrm{d}t)/m, \tag{26}$$

where the particle mass is given by

$$m = \frac{3}{4} \cdot \pi \cdot \rho_\mathrm{i} \cdot r^3, \tag{27}$$

with ρ_i (kg m^{-3}) being ice density and r (m) representing the radius of a spherical ice particle (assumed to be 500 µm as proposed by Liston and Elder, 2006b).

Mass loss from an ice particle is described as a function of intercepted solar radiation, humidity gradients between the ice surface and the surrounding atmosphere, the size of the considered ice particle and a ventilation term, following Thorpe and Mason (1966) and Schmidt (1972):

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{2 \cdot \pi \left(\frac{\mathrm{RH}}{100}\right) - S_\mathrm{p} \cdot \Omega}{h_\mathrm{s} \cdot \Omega + \frac{1}{D \cdot \rho_\mathrm{v} \cdot S \cdot h}}, \tag{28}$$

where h_s is the latent heat of sublimation (2.8355×10^6 J kg^{-1}).

The diffusivity of water vapour in the atmosphere, D (m^2 s^{-1}) is derived following Thorpe and Mason (1966) as:

$$D = 2.06 \cdot 10^{-5} (T_\mathrm{a}/273)^{1.75}. \tag{29}$$

The molecular weight of water M (18.01 kg kmole^{-1}), the universal gas constant R (8313 J kmole^{-1} K^{-1}), air temperature T_a (K) and the thermal conductivity of the atmosphere λ_t (0.024 J m^{-1} s^{-1} K^{-1}) are used to calculate Ω as proposed by Liston and Elder (2006b):

$$\Omega = \frac{1}{\lambda_\mathrm{t} \cdot T_\mathrm{a} \cdot \mathit{Nu}} \cdot \left(\frac{h_\mathrm{s} \cdot M}{R \cdot T_\mathrm{a}} - 1 \right). \tag{30}$$

The Nusselt number *Nu* and Sherwood number *Sh* are both calculated as:

$$\mathit{Nu} = \mathit{Sh} = 1.79 + 0.606 \cdot \mathit{Re}^{0.5}, \tag{31}$$

where *Re* $(0.7 < \mathit{Re} < 10)$ is the Reynolds number expressed by:

$$\mathit{Re} = \frac{2 \cdot r \cdot u_\mathrm{c}}{v} \tag{32}$$

with v representing the kinematic viscosity of air $(1.3 \cdot 10^{-5}$ m^2 s$^{-1})$ and u_c the ventilation velocity inside the canopy, which is set equal to inside-canopy wind speed as proposed by Liston and Elder (2006b).

Following Fleagle and Businger (1981) the saturation density of water vapor ρ_v (kg m^{-3}) is derived as

$$\rho_\mathrm{v} = 0.622 \cdot \frac{e_\mathrm{s}}{R_\mathrm{d} \cdot T_\mathrm{a}} \tag{33}$$

where R_d is the gas constant for dry air (287 J K^{-1} kg^{-1}) and e_s (Pa) is the saturation vapor pressure over ice, estimated following Buck (1981) as:

$$e_\mathrm{s} = 611.15 \exp \left(\frac{22.452 \cdot (T_\mathrm{a} - 273.16)}{T_\mathrm{a} - 0.61} \right). \tag{34}$$

The shortwave radiation absorbed by a snow particle with radius r is defined to be

$$S_\mathrm{p} = \pi \cdot r^2 (1 - \alpha_\mathrm{p}) \cdot S_\mathrm{i}, \tag{35}$$

where α_p is the snow albedo, and S_i (W m^2) is the solar radiation at the earth surface, which in case of ESCIMO.spread (v2) is among the required meteorological input parameters.

To account for a melt-induced unloading of intercepted snow from the canopy, a melt-unloading rate L_m (kg m^{-2}) is introduced by Liston and Elder (2006b):

$$L_\mathsf{m} = 5.8 \cdot 10^{-5} (T_\mathsf{a} - 273.16) \cdot \mathrm{d}t. \tag{36}$$

We assume an unloading rate of 5 kg m^{-2} day^{-1} K^{-1} whenever temperatures are above freezing, with unloading snow adding to snow accumulation at the land surface. The simulated filling and depletion of the interception storage through snow fall, sublimation and melt induced unload is illustrated in Fig. 4 exemplarily for a period in February 2013.

3 Data and test site description

Snow cover simulations in this study are carried out for the forest site Vordersteinwald in the Black Forest mountain range (south-west Germany) (see Fig. 1). This site is eminently suitable for testing of the newly developed version of ESCIMO.spread as it (i) usually experiences alternation of accumulation and melting periods over the winter season, making the simulation of snow conditions particularly demanding and (ii) has been subject to intense snow surveys over the years 2010–present, including simultaneous observation of meteorological and snow conditions in and outside the forest canopy (Pohl et al., 2014).

The forest stand at the study site is mostly conifer with spruce, fir and pine, representing the most common conifer tree species. To quantify the vegetation effect on snow conditions, the applied snow monitoring systems (SnoMoS) were installed pairwise with one SnoMoS located in the open and another set up in close distance inside the forest canopy (see Fig. 5). The data recorded by these low-cost monitoring sensors include hourly values of snow depth, surface temperature, air temperature and humidity, global radiation, wind speed, and barometric pressure.

The continuous monitoring of snow depth with the SnoMoS was accompanied by biweekly snow density surveys that allow translation of snow depth into SWE. A comprehensive description of the technical specifications and the instrumental setup of the SnoMoS is provided by Pohl et al. (2014). Precipitation recordings for the study site originate from nearby weather station Freudenstadt (DWD, 2015), operated by the German Weather Service (DWD). Precipitation observations have been corrected for differences in terrain elevation between the sites of measurement and model application by applying monthly elevation adjustment factors as proposed by Liston and Elder (2006a). The latter have been taken from Marke (2008) who has investigated altitudinal differences in precipitation for the Upper Danube Watershed. No interpolation using other station data has been carried out due to the closeness of the study site (3 km distance) to station Freudenstadt. Hemispherical images were taken at the forest location and were utilized to derive the effective LAI of the forest stand ($\text{LAI}^* = 2.6\,\text{m}^2\,\text{m}^{-2}$). Moreover, a logarithmic function considering snow ageing and new snowfall was used to compute daily snow densities between the surveys. All data used as model input and for model validation are freely provided along with the model.

4 Results

ESCIMO.spread (v2) has been applied to modify outside-canopy meteorological conditions for canopy effects at site Vordersteinwald as well as for a subsequent simulation of the SWE evolution for the winter season 2012/2013. Figure 6 shows outside-canopy global radiation modified for canopy effects with the new ESCIMO.spread (v2) algorithms in comparison to inside-canopy observations. As global radiation under mid-latitude prealpine conditions usually provides the largest share of energy for snow melt, an accurate representation of inside-forest global radiation is essential for a realistic reproduction of snow ablation with any energy balance model. The general dimension and temporal variation in global radiation inside the forest canopy seem well reproduced with a certain tendency of the model to underestimate global radiation in the forest. The latter is also reflected by the scatter plot shown in Fig. 10 opposing simulated and observed global radiation. The satisfactory overall model performance in the modification of global radiation for canopy effects is also confirmed by the high values of the coefficient of determination (R^2 = 0.66), the Nash Sutcliffe model efficiency (NSME = 0.64) and the index of agreement (IA = 0.89) as well as by the low root mean square error (RMSE = 8.23 $\mathrm{W\,m^{-2}}$) (see Krause et al., 2005 for a detailed explanation of the efficiency criteria applied). The values of these efficiency criteria are provided in Tab. 1 with the corresponding scatter plots for all meteorological input variables modified for canopy effects shown in Fig. 10. As shown in Fig. 7, the simulated and observed courses of temperature match fairly well until late January, whereas the simulations overestimate daily temperature peaks in spring. The efficiency criteria of R^2, NSME, IA and RMSE with values of 0.79, 0.82, 0.94 and 1.74 (K), respectively, further underline the good performance of ESCIMO.spread (v2) with respect to the modification of outside-canopy temperature conditions. Compared to global radiation and temperature, the model performance for relative humidity and wind speed with R^2 and IA values in the order of 0.6 and 0.7–0.8 for both criteria, respectively, is distinctly weaker. In case of both variables the NSME with values below 0 indicates that the mean value of the observations would be a better predictor than the model (Krause et al., 2005). The course of relative humidity and wind speed conditions illustrated in Figs. 8 and 9 explains the diametrical picture of model performance described by means of R^2 and IA compared to NSME. While the temporal variation in relative humidity and wind speed is well reflected in the simulations (resulting in good correlation and acceptable values of R^2 and IA), the exact values in the observed time series are seldomly reproduced by the model results, a condition that is considered in the calculation of NSME (Krause et al., 2005). The high temporal and spatial variability in wind speed naturally makes any spatial interpolation or modification for canopy effects particularly challenging. ~~In case of both variables, the simulations tend to exceed observed values of humidity and wind speed in the forest canopy.~~ In case of both variables, higher maximum values can be observed in the simulated time series.

The good overall model performance as well as the differences in model performance for the different meteorological variables might at least partly be explainable by the presence/absence of pronounced daily cycles in the hourly values. While systematic daily variations in the temperature and global radiation data can be expected to bias some efficiency criteria towards higher model performance, the lower model performance for wind speed and relative humidity might partly be due to weaker or missing daily cycles in the analyzed data. To further look into these assumptions, the predictive capabilities of outside-canopy observations for the estimation of inside-canopy conditions are provided in Tab. 2. Comparing the values of the different efficiency criteria calculated for the four meteorological variables to those shown in Tab. 1 reveals that while values of R^2 are equally high for all meteorological variables, the significant increase in NSME values clearly shows the improvements resulting from application of the canopy model, particularly when estimating global radiation inside the forest canopy. Only in case of relative humidity, the outside-canopy measurerements seem to slightly better predict inside-canopy conditions. This can be explained by the fact that looking at the SnoMoS data for the winter season 2012/2013, measured humidity outside the canopy is often higher than that observed inside the forest stand, whereas the canopy model in ESCIMO.spread (v2) increases outside-canopy humidity with consideration of the canopy fraction to estimate inside-canopy relative humidity (see Eq. 21).

The simulated snow cover is displayed in Fig. 11 for the open and in Fig. 12 for inside the canopy in comparison to observations at the respective sites. As can be seen from Fig. 11, the newly developed version ESCIMO.spread (v2) much better reproduces the observed snow conditions outside the forest at site Vordersteinwald compared to ESCIMO.spread (v1). This increase in model performance is mostly due to the fact that liquid precipitation in ESCIMO.spread (v1) increases SWE by the total value of observed precipitation, whereas in the new model version liquid precipitation is only added to the SWE up to a maximum value defined by the water holding capacity with the rest leaving the snow pack as outflow (see Eq. 11). While these improvements are less important for simulations at high alpine sites, where the largest share of precipitation in the winter season falls in form of snow (see Strasser and Marke (2010)), at lower elevated sites the comparatively high amounts of liquid precipitation in winter make these model modifications essential. As a result of these further developments, the severe overestimation in simulated SWE observed in the results of ESCIMO.spread (v1) is no longer found in the results of ESCIMO.spread (v2) leading to a significant increase in model performance as confirmed by the values of the different efficiency criteria in Tab. 3. The simulations carried out with ESCIMO.spread (v2) sometimes even show a tendency to underestimate observed snow conditions for the winter season 2012/2013, particularly with respect to the second snow peak at site Vordersteinwald in February 2013. Looking at the results achieved for inside the canopy (see Fig. 12 and Tab. 3), applying the canopy model allows to reasonably reproduce observed snow conditions inside the forest. Compared to the results achieved using observed outside-canopy snow conditions as a predictor for inside-canopy snow conditions (see Tab. 2), application of the proposed canopy model increases NSME values from - 0.49 to 0.81 and reduces RMSE from 23.07 to 8.26 mm.

The fact that the model results inside the canopy are even better than for the outside (see also the scatter plots in Fig. 13), might at least partly be the result of multiple error compensation effects (including errors from precipitation measurement, the transfer of precipitation information from precipitation gauge Freudenstadt to site Vordersteinwald as well as from translating snow depth into SWE). The green line in Fig. 12 shows the simulations achieved using observed meteorological conditions inside the canopy (as provided by the SnoMoS inside the forest). Due to a lack of precipitation recordings inside the forest, the precipitation data used as input for the simulations inside the canopy in this experiment also represent recordings from station Freudenstadt modified for canopy effects. Hence, precipitation inside the canopy as used as input for the snow simulations has to be considered a model result rather than an observation. The same applies to the incoming component of inside canopy longwave radiation, which to a certain fraction represents the simulated top-of-canopy incoming longwave radiation due to a lack of observations outside the forest stand (see Eq. 18 and explanations below). Comparing the results achieved using observed and simulated meteorological conditions inside the forest as model input (see Fig. 12), the meteorological observations allow only slightly better model performance with NSME increasing from 0.81 to 0.82 and RMSE decreasing from 8.26 to 8.02 mm. The results of both model runs show a distinct overestimation of SWE between 15 and 26 December. A closer look at the conditions during this period reveals significant snowfall at temperatures close to 0 °C and air humidity close to saturation. Hence, an explanation for the observed overestimation of SWE in this period might be a false interpretation of liquid precipitation as solid precipitation. While the model acceptably reproduces snow accumulation between 10 and 30 January in the open, a noticeable overestimation of SWE can be observed in the results using the modified outside-canopy meteorological conditions. Moreover, a period of snow accumulation can be observed in the observations and simulations for the open in March, whereas inside the canopy this increase in SWE is merely predicted by the model and not confirmed by the observations. ~~A comparison of the snow simulations based on observed and simulated meteorological conditions inside the canopy reveals that only little differences exist between both model runs, with the model performance using observed meteorological conditions as model input being slightly better. Taking a closer look at the efficiency criteria in Tab. 3, the model results for both locations seem to well reflect the observed conditions with model performance inside the canopy beeing even slightly better than in the open.~~

5 Conclusions

A new version of the spreadsheet-based point energy balance snow model ESCIMO.spread has been presented (ESCIMO.spread (v2)) that allows an improved precipitation phase detection, estimation of snow temperature, consideration of cold and liquid water content in the snow cover, estimation of inside canopy meteorological conditions from meteorological observations in the open and the simulation of snow accumulation and ablation inside a forest canopy. It thereby does not require meteorological observations in the canopy but instead derives inside-canopy meteorological conditions from available observations in the open requiring only LAI and canopy height as plant-specific input parameters. The derived meteorological conditions inside the canopy are not only applicable as input for snow cover simulations but can be expected to be of interest for a variety of scientific disciplines, e.g. forest ecology or pedology. To provide the data required for model application and evaluation, a pair of SnoMoS has been utilized as an innovative technology that allows the collection of important meteorological variables at low financial costs. Comparison of simulated inside-canopy meteorological conditions to observations at a site in the Black Forest region

(Germany) reveals good overall model performance, particularly with respect to global radiation (NSME = 0.64, RMSE = 8.23 W m^{-2}) and temperature (NSME = 0.79, RMSE = 1.74 K) representing the most important meteorological variables for the estimation of snow melt. In case of relative humidity and wind speed the model efficiency with NSME values of -1.10 and -0.29 and an RMSE of 6.31 % and 0.59 m/s for the two variables, respectively, was noticeably lower. This lower model performance might at least partly be the result of weaker or missing daily cycles in the hourly data as well as potential biases in the measurements of the applied low cost monitoring systems, which are described in detail by Pohl et al. (2014). A satisfactory model performance unfolds when comparing the simulated snow cover evolution in- and outside the canopy to snow observations provided by the SnoMoS. NSME here reaches values of 0.81 and 0.71 with an RMSE of 8.26 and 18.07 mm for simulated SWE in- and outside the canopy, respectively. While snow cover evolution is well reproduced for both, out- and inside the forest canopy, model performance is slightly higher for inside-canopy conditions, even though the empirical model parameters have not yet been adjusted to (pre)alpine forest species. This might at least partly be explainable by multiple error compensation effects (including errors from precipitation measurement, the transfer of precipitation information from precipitation gauge Freudenstadt to site Vordersteinwald and the translation from snow depth to SWE). Making use of the full potential of simultaneous observation of snow and meteorological conditions as provided by the SnoMoS, an effort is currently undertaken to develop parameters for the applied canopy model that are tailored to the specific conditions in (pre)alpine forests. Moreover, despite its physically-based character and advanced model features, ESCIMO.spread (v2) still oversimplifies some important processes of the snow-vegetation interaction. In the current version the model only considers unloading of intercepted snow as a result of melting. While the fact that wind also induces unloading of intercepted snow is well known, the combined dependence on plant characteristics (e.g. plant structure and plant element flexibility) and meteorological conditions (e.g. snow temperature, wind speed and direction) makes this a complex process hard to consider in numerical models (Liston and Elder, 2006b). The modification of shortwave and longwave radiation assumes a plant specific extinction coefficient and a constant canopy fraction, respectively. While these assumptions can be expected to reasonably reproduce the general observed patterns in local radiation, they are not capable to accurately capture the actual radiation conditions whenever canopy densities strongly vary or sun is shining through open areas in the trees as a result of changing solar zenith angles.

Code availability

ESCIMO.spread (v2) can be downloaded free of charge at www.alpinehydroclimatology.net together with one year of sample data including the meteorological and snow observations used in this study. The model has been tested on OpenOffice 4.1.1. as well as on different versions of Microsoft Excel for Windows and Mac.

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Table 1. Performance of ESCIMO.spread (v2) in the modification of outside-canopy global radiation, temperature, relative humidity and wind speed for canopy effects.

Variable	NSME	R^2	IA	RMSE
Global radiation	0.64	0.66	0.89	8.23 (W/m^2)
Air temperature	0.79	0.82	0.94	1.74 (K)
Relative humidity	-1.10	0.61	0.74	6.31 (%)
Wind speed	-0.29	0.60	0.80	0.59 (m/s)

Table 2. Predictive capabilities of outside-canopy observations for inside-canopy conditions.

Variable	NSME	R^2	IA	RMSE
Global radiation	-28.24	0.66	0.39	73.79 (W/m^2)
Air temperature	0.74	0.85	0.95	1.92 (K)
Relative humidity	-0.81	0.65	0.76	5.84 (%)
Wind speed	-13.66	0.60	0.48	2.01 (m/s)
SWE	-0.49	0.87	0.82	23.07 (mm)

Table 3. Performance of ESCIMO.spread (v1) and ESCIMO.spread (v2) at site Vordersteinwald for the winter 2012/2013. As ESCIMO.spread (v1) does not include formulations of inside-canopy processes, model performance for inside-canopy conditions is only available for ESCIMO.spread (v2). The simulations inside the canopy are based on modified outside-canopy meteorological conditions.

Variable	NSME	R^2	IA	RMSE
SWE (v1) outside canopy	-15.20	0.34	0.37	134.28 (mm)
SWE (v2) outside canopy	0.71	0.81	0.90	18.07 (mm)
SWE (v2) inside canopy	0.81	0.83	0.95	8.26 (mm)

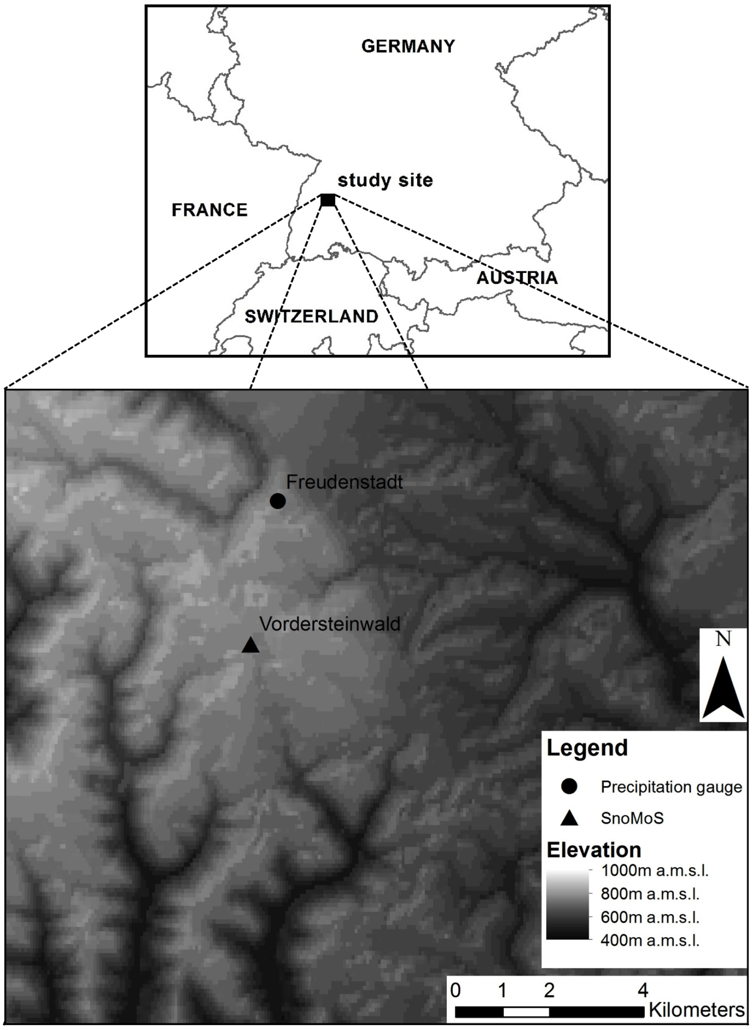

Figure 1. The site Vordersteinwald in the Black Forest mountain range (south-west Germany, 800 m a.s.l).

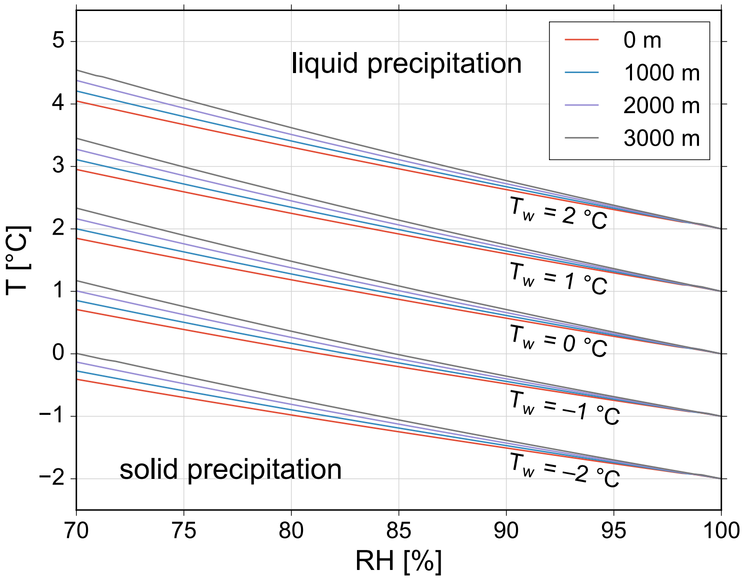

Figure 2. Relation between air temperature, wet-bulb temperature and relative humidity in different altitudes. The latter represent different air pressure levels derived using the hydrostatic equation. The colored lines can be interpreted as borderlines to separate liquid and solid precipitation assuming a certain threshold wet-bulb temperature.

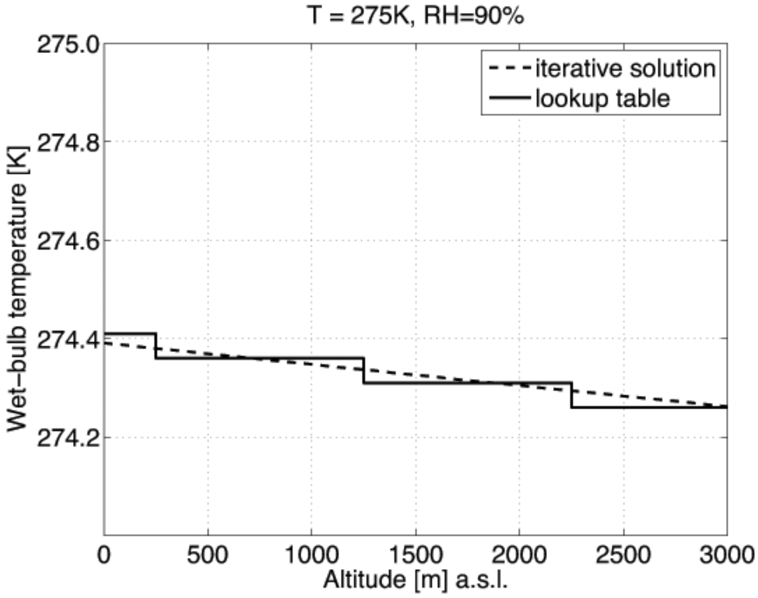

Figure 3. Comparison of iteratively calculated wet bulb temperature to the results of the lookup table approach implemented in ESCIMO.spread (v2).

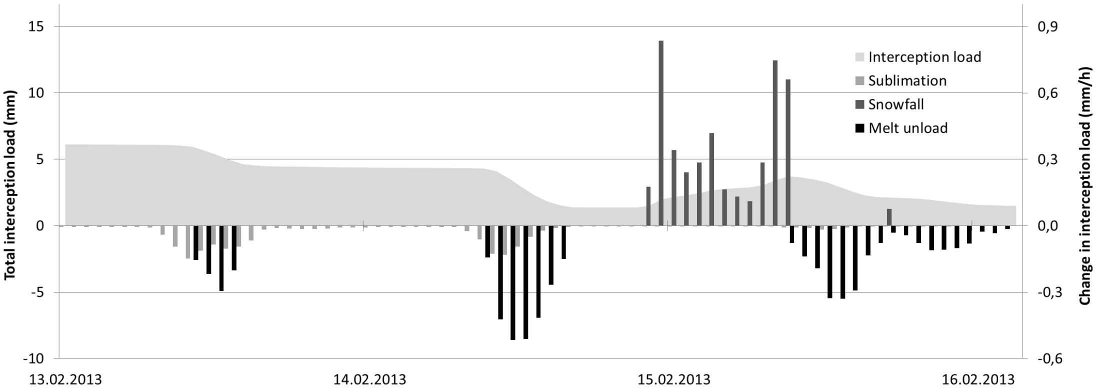

Figure 4. Simulated filling and depletion of the interception storage through snowfall, sublimation and melt induced unload at site Vordersteinwald in the Black Forest mountain range (south-west Germany).

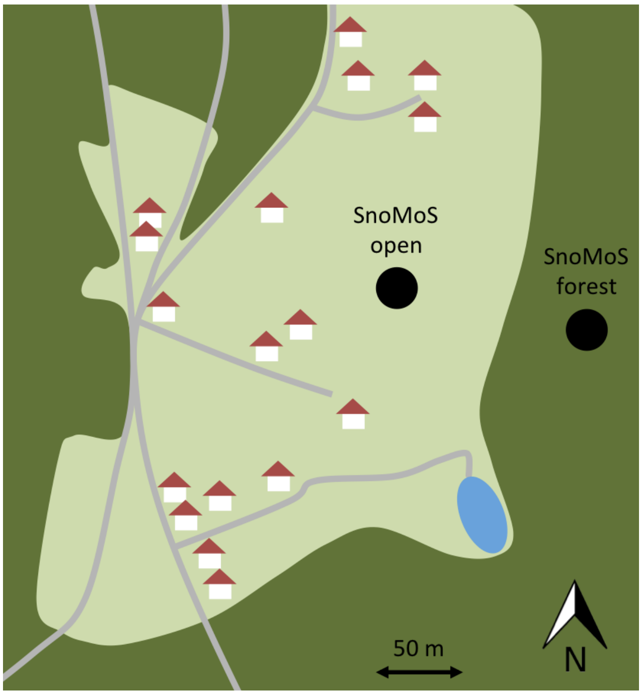

Figure 5. Schematic overview of the SnoMoS setup locations in- and outside the forest canopy at site Vordersteinwald in the Black Forest mountain range (south-west Germany, 800 m a.s.l). The light green areas indicate grassland, the dark green areas forest, the grey lines streets and the light blue area a lake.

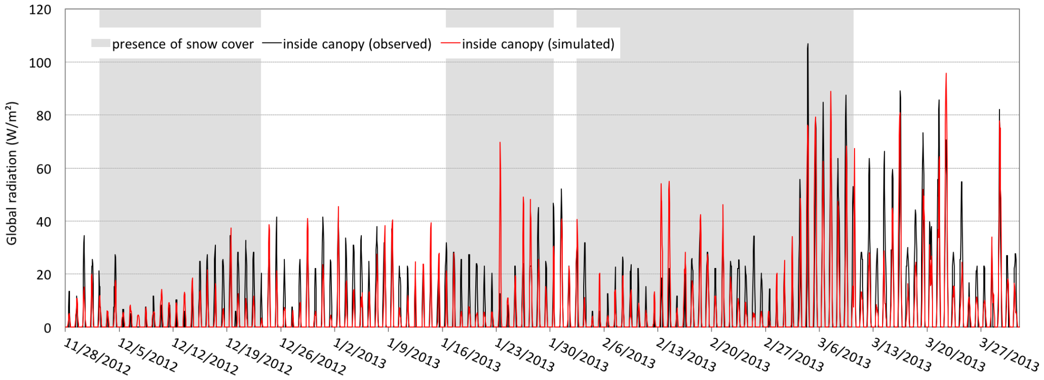

Figure 6. Simulated and observed global radiation for the winter period 2012/13 at site Vordersteinwald. The grey areas indicate periods with presence of a snow cover.

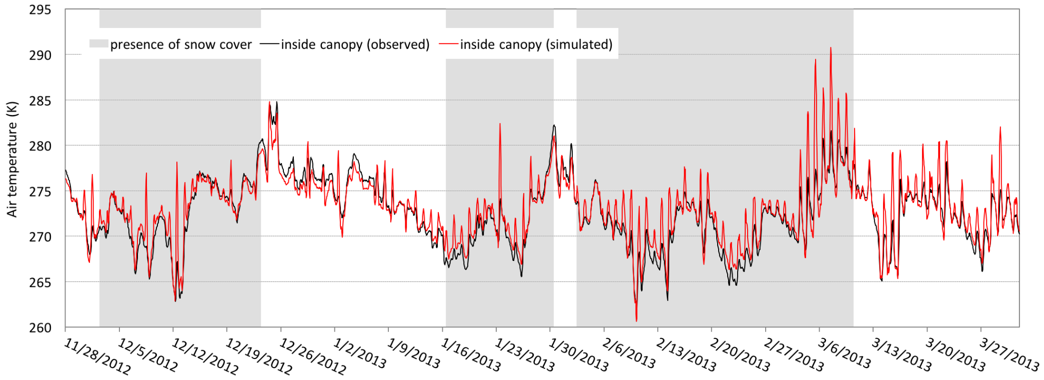

Figure 7. Simulated and observed temperature inside the forest canopy for the winter period 2012/13 at site Vordersteinwald. The grey areas indicate periods with presence of a snow cover.

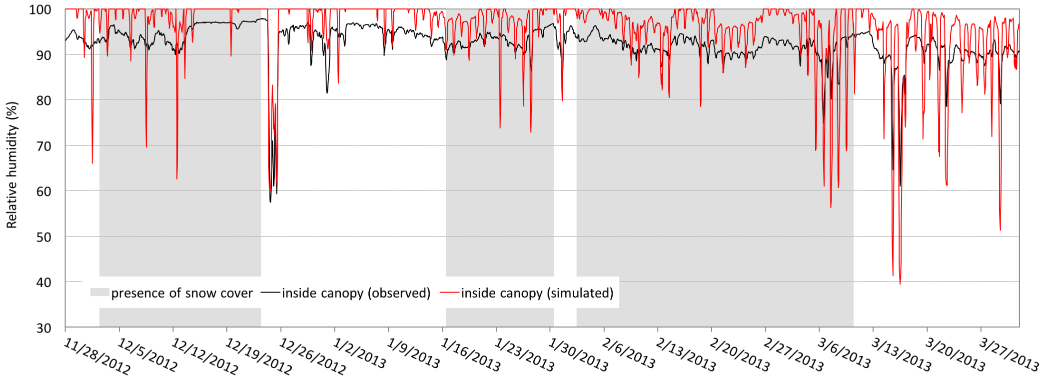

Figure 8. Simulated and observed relative humidity inside the forest canopy for the winter period 2012/13 at site Vordersteinwald. The grey areas indicate periods with presence of a snow cover.

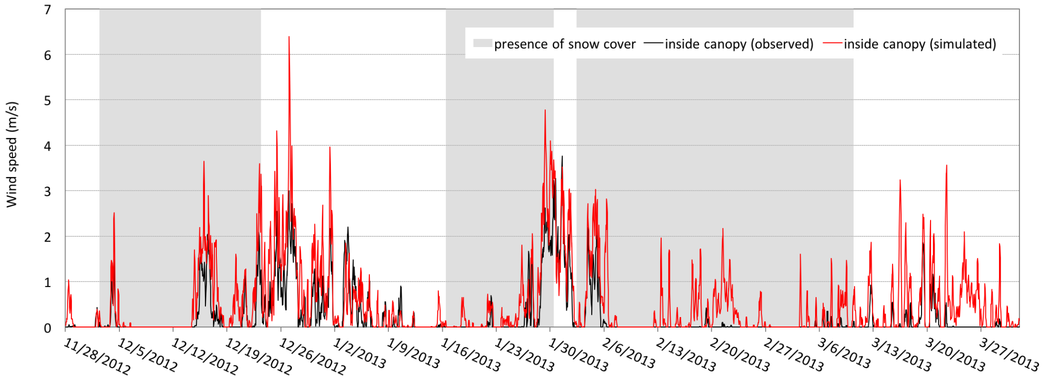

Figure 9. Simulated and observed wind speed inside the forest canopy for the winter period 2012/13 at site Vordersteinwald. The grey areas indicate periods with presence of a snow cover.

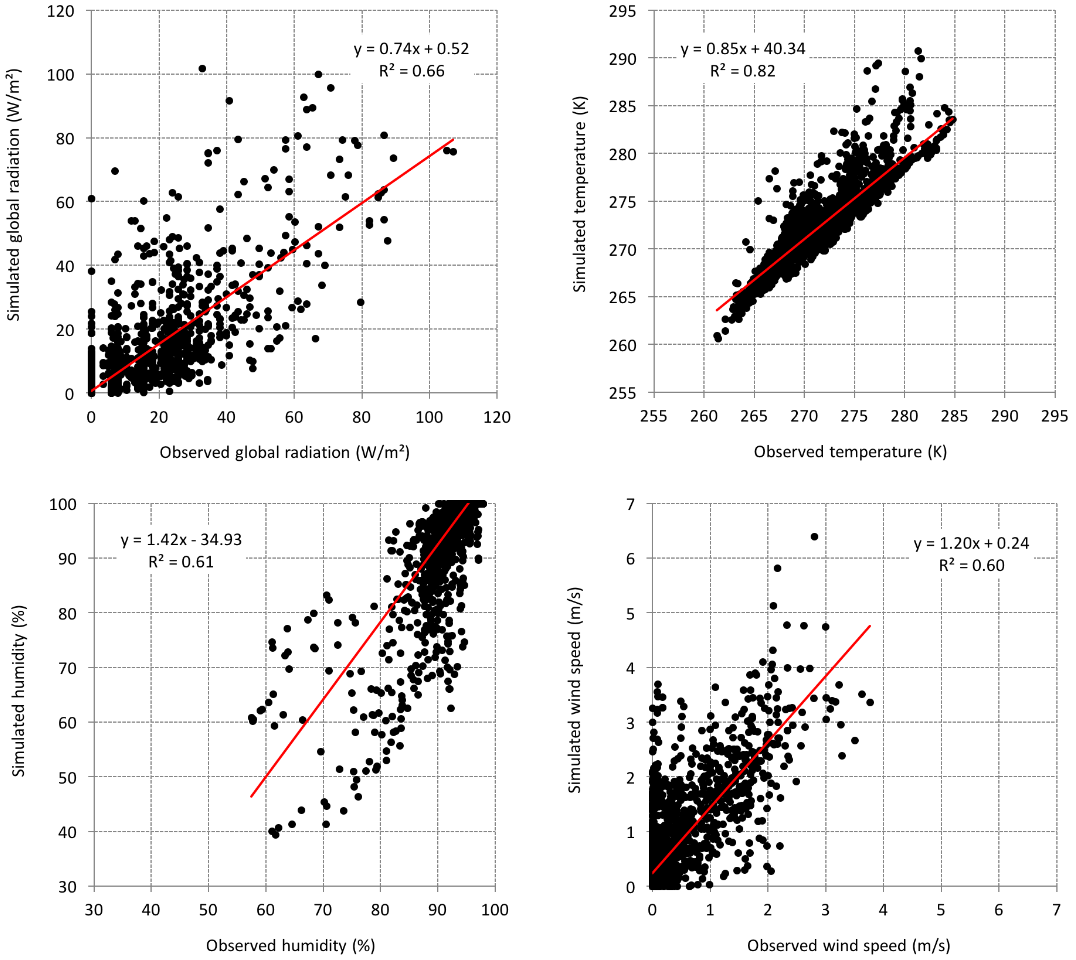

Figure 10. Simulated vs observed meteorological conditions inside the forest canopy for the winter period 2012/13 at site Vordersteinwald.

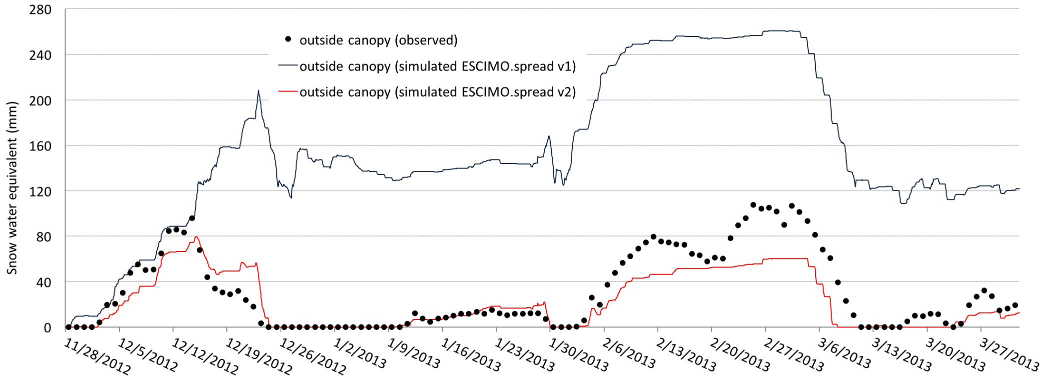

Figure 11. Simulated and observed snow water equivalent outside the forest canopy for the winter period 2012/13 at site Vordersteinwald. The blue and the red line represent the results achieved with the previous (v1) and the newly developed version (v2) of the ESCIMO.spread model, respectively.

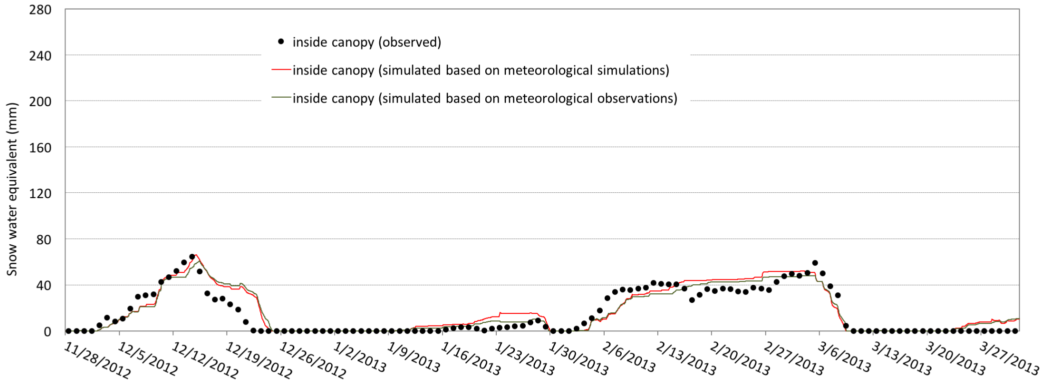

Figure 12. Simulated and observed snow water equivalent inside the forest canopy for the winter period 2012/13 at site Vordersteinwald. The two curves illustrate the snow simulations achieved with the parameterized (red) and observed (green) meteorological conditions inside the canopy.

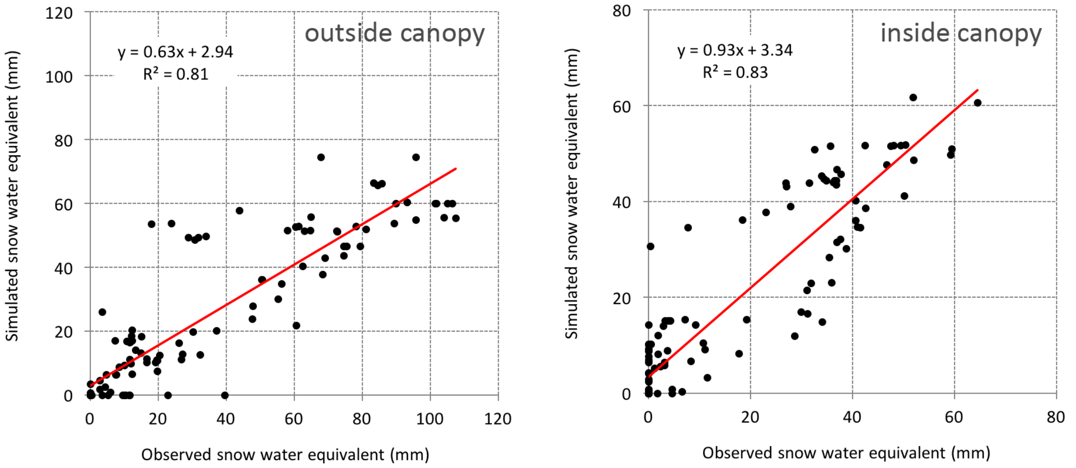

Figure 13. Snow water equivalent simulated with ESCIMO.spread (v2) vs observed snow conditions out- and inside the forest canopy for the winter period 2012/13 at site Vordersteinwald.